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## Physical Modeling of Suspended Sediment Deposition in Marine Intakes of Nuclear Power Plants

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### Abstract

This paper deals with the problems associated with the design and operation of once-through or combined water cooling systems of nuclear power plants using sea water. Suggested refinement techniques of physical modeling of hydraulic processes at the pre-stage using multipurpose hydraulic stand. An example of such a construction of the stand and the experience of its use in the justification of the design decisions of waterworks of energy facilities.

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### 1. Introduction

Currently, many countries have placed nuclear power plants on the coasts, using seawater cooling systems [1–4]. The reasons for this are:

1. Freshwater is an important natural resource for many countries of the world, which determines the efforts to quantify its rational use and protection of its quality. Therefore is undesirable to use it for cooling of NPP reactors.

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2. As opposed to thermal power stations the placement of NPP is not depending on the location of the fuel sources, and it is determined firstly by the energy consumers location, and secondly by the presence of the water for cooling.

In line with this, many countries place nuclear power plants on the coast, which is often caused by a great need for energy due to the higher level of economic development of coastal regions, as well as by the possibility of using seawater for cooling.

In 2011, about 40% of operating nuclear reactors in the world (179 of 454) used seawater for the cooling [5]. In the US there were 20 of them out of 104, in Canada – 1 of 22, in China – 12 out of 13. A number of countries used for reactors' cooling exclusively seawater: Japan – 48, Korea – 21, United Kingdom – 19, Taiwan – 6. Presumably, the number of nuclear reactors, which use for cooling seawater, will increase, as well as the number of thermal power plants, using seawater for cooling.

The advantages of NPP, using seawater cooling systems are:

1. Saving significant amounts of freshwater;
2. The sufficient amount of water for cooling purposes;
3. The better conditions of allotment of a large amount of heat, generated in the cooling process, due to the large volume of water in the sea areas, and better water exchange due the tidal and wave processes.

However, it should be noted that the factors, mentioned in paragraph 3, require serious consideration, because the temperature increase can lead to eutrophication of the coastal zone. Tidal, wave phenomena and coastal currents lead to significant level fluctuations and turbidity of sediments in the coastal zone [6, 7], followed by possible sediments deposition in water intakes and water conducting structures of the cooling system. These issues must be considered during predesign research and design works, as well as the presence of algae, shellfish and microflora in seawater.

NPP water cooling systems, as well as all the stations as a whole, are the unique structures due to the difference of technical solutions and environmental conditions (climatic, geological, topographical, hydrological, etc.). Therefore, the use of standard solutions is only possible when considering of the sketch. Design decisions should be based on the results of predesign research works. It can be achieved by bringing together research and design organizations during the mathematical and physical modeling.

The improvement of the efficiency and safety requirements for hydrotechnical constructions of hydropower, nuclear and thermal power stations demands more careful consideration and justification of design solutions [8–10].

There are two methods of modeling of hydraulic phenomena: mathematical [11–14] and physical [15, 16] modeling.

Currently, different software packages, implementing mathematical models approved for most cases encountered in practice: Flow 3D, Mike11 [17, 18] and others, are widely used for the design study project alternatives. Application of these programs can significantly reduce the time and financial resources, required for the design. However, in many cases, due to the uncertainties in the flow setting of many parameters of the models, the direct use of numerical models (implemented in application packages) is inefficient, difficult, or even impossible, particularly, for the calculation of three-dimensional circuitry with complex problems.

To solve these problems it is necessary to resort to physical modeling. The basis of physical modeling phenomena are methods of similarity and dimensions theory. They allow you to make the dimensionless equations describing physical phenomena with a significant reduction of the dimension of the factor space.

## **2. Simulation of fluid flow in the main supply chamber.**

The problem of physical simulation of suspended matter motion carried by fluid in water bearing structures of the building cooling water pumps for important NPP consumers, is rather complicated [19–22]. First, you need to provide kinematic and dynamic similarity of flows in prototype and models if they are strict geometrically similar. In physical modeling the kinematic and physical similarity of model and full-scale flows is achieved when the numbers of similarity in the prototype and in the model are equal. At the same time it means equality of ratios of the same forces, acting in the model and in prototype. If the motion of a Newtonian fluid is stationary, three similarity numbers determine the phenomenon: Reynolds, Froude and Euler (simultaneously it means equality of the same forces ratios in the model and in prototype: friction and inertia, inertia and gravity based on the Archimedes force,

pressure and inertia, respectively). However, to ensure the equality of all numbers of similarity in the model and in prototype is impossible because the requirements for the simulation results, arising from the equality of numbers similarity, are incompatible. For example, if the equality of Froude numbers is:

$$Fr_p = Fr_m, \quad u_p^2 / g_p l_p = u_m^2 / g_m l_m \quad (1)$$

the indicator of similarity should be:

$$k_u^2 / k_g k_l = 1 \quad (2)$$

where  $k_u = u_p / u_m$  is the velocity scale factor,  $k_l = l_p / l_m$  is a scale factor of the linear dimensions,  $k_g$  is a scale gravity factor. If conditions in the model and in prototype occur in the field of Earth's gravitational force, the  $k_g = 1$ , hence, using an indicator of similarity we'll obtain the connection between scale factors of speed and linear dimensions:

$$k_u = \sqrt{k_l} \quad (3)$$

If the equality of Reynolds numbers is

$$Re_p = Re_m, \quad u_p l_p / \nu_p = u_m l_m / \nu_m \quad (4)$$

the indicator of similarity should be  $k_u k_l / k_\nu = 1$ , where  $k_\nu$  is a scale factor of kinematic viscosity of water. If the liquid in the model and in prototype is the same, then  $k_\nu = 1$ , hence the relationship between scale factors of speed and of linear dimensions should be:

$$k_u = 1 / k_l \quad (5)$$

It turns out that if modelling "by Frode" the liquid velocity in the model should be less than in prototype (in  $\sqrt{k_l}$  times); if modelling "by Reynolds" the liquid velocity in model should be greater than in prototype (in  $k_l$  times) – such the requirements are incompatible. In this case, one of the most simple, but sufficiently rigorous methods for the approximate simulation can be used. We use the basic property of the quadratic resistance zone of turbulent region – the independence of the coefficient of hydraulic friction (or the Euler number) from Reynolds criterion. If the Reynolds number in the model at the edge of the quadratic resistance is equal  $Re_b$ , then in the case of equality of relative roughness, the coefficients of hydraulic friction in the model and in prototype will match. Therefore, the equality of Euler numbers, which are equal to the coefficient of hydraulic friction up to a constant, will be ensured.

Meanwhile, the flow velocity in the clean water chamber of responsible consumers in power unit is small. The Reynolds number in prototype is small. When modeling "by Frode" the Reynolds number in the model is reduced in  $k_l^{1.5}$  times compared to the prototype. As a result, the Reynolds number in the model may be less than the limit value, a phenomenon in the model will concern the hydraulically smooth bed zone or transition zone. In these areas the laws of resistance are different than those in quadratic resistance zone, Euler equation will not be reached, so the phenomenon occurred in the model will not be kinematically and dynamically similar to such in prototype. While modelling "by Reynolds" the Froude number in the model will increase in  $k_l^3$  times comparatively with prototype, causing the flow in the model may be rough, while in prototype it is quiet, but these are two different phenomena.

To overcome these contradictions, the different methods of hydraulic phenomena approximate simulation are developed and widely used in various investigations.

One of these methods of approximate simulation is to increase the model flow rate compared to the rate, which is dictated by the terms of modeling "by Frode" (method is called "forcing the flow velocity or flow of water"). Such modeling method can be used when the flow rate in the model is less than non-blurry, while in the prototype the flow rate exceeds the non-blurry. This happens because the non-blurry flow velocity primarily for fine-grained material is not recalculated to full-scale conditions in the model according to the indicator of similarity arising from the equality of Froude numbers. For such materials, non-blurry flow velocity in the model differs little from the corresponding rate in prototype. It was then necessary to resort to the method of forcing the flow velocity. However, the method requires corrections. First of all, it must be ensured that the Froude number in the model did not work outside the self-field in which the phenomenon is independent of the number. Furthermore, the ratio of the flow rate pattern to a non-blurry (called "mobility factor of particulate material") must be the same when the flow rate exceeds the non-blurry, and when it is less than a non-blurry. And finally, with this method of modeling the phenomenon in the model can be in different area of resistance than in prototype, why the equality of the coefficients of hydraulic friction (or Euler numbers) will be violated. For example, in prototype, the phenomenon relates to the quadratic resistance zone, and in the model (even using the method of forcing velocity) it remains in hydraulically smooth bed or transition zone. In this case it is necessary to use another method of approximate modeling, wherein the equation of hydraulic friction coefficients can be provided by selecting a value of relative roughness in the model.

Simulation methodology is described in detail in [23].

Summarizing, we can say that for the fluid flow in the main water supply chamber of pumps building for cooling water for responsible NPP consumers a method for the approximate hydraulic modeling has been proposed, the essence of which is contained in the following provisions. Froude number in the model exceeds this number in prototype, but does not go beyond the self-field. By selecting a flow rate in the model (exceeding the flow speed in prototype by 25%) and the corresponding Reynolds number the flow in the model was succeeded to transfer from hydraulically smooth channel to transition zone. This ensured the equality of the coefficients of hydraulic friction (and Euler equations) on the bottom of streams in prototype and in the model.

### 3. Laboratory stand and methodology for conducting experiments.

Figure 1 shows a diagram of the laboratory bench, which hosts a model of one section of water intake structures. Stand includes reservoir for water recycling 1 located under the floor of the lab, and a pumping station 2. By the water pump station water is fed into the pressurized water distribution tank 3. Hydraulic tray 5 has a length of about  $15m$ , its width is equal to  $0,6m$ . Section of intake structures drawn to scale  $1/5$  natural size (linear scale factor  $k_l = l_p / l_m = 5$ , where  $l_p$  and  $l_m$  – linear dimensions in prototype and in the model, respectively). The main supply chamber is divided into three compartments via booms, the distance between the boom axes is  $12.6m$  in prototype and about  $2.5m$  in model. At the head of the tray, which receives water from a pressurized water distribution tank 3, there is a hopper 7 for supplying the suspended sediments in the water. In the center of the tray there is a model of intake chamber 8. The intake chamber model is made of thick transparent plastic.

Inside the intake chamber model two pipelines originate (by the number of pump units supply cooling seawater to responsible consumers). They are combined into a single one 11 outside power unit, which is installed on the suction line of the pump, the pump pressure line is connected to the reservoir for water recycling 1. Each of the two pipes has valves that allow to connect one of them to the conduit 11 or to disconnect them from the pipeline. Thus the model reproduces a water intake by pumps located in the intake chamber, or blackout intake chamber from participation in water supply responsible consumers of water.

Glazed laboratory tray, which hosts the main model of supply chamber, has the mounted gate 12 at the end part. With the gate in the tray, one can set a certain level of water. Thus, a model that includes the main supply chamber and one intake chamber, one can explore a variety of situations related to the operation of water intake tract from pure water chamber to its responsible customers and in the first place, to explore deposits sedimentation in different parts of the tract.

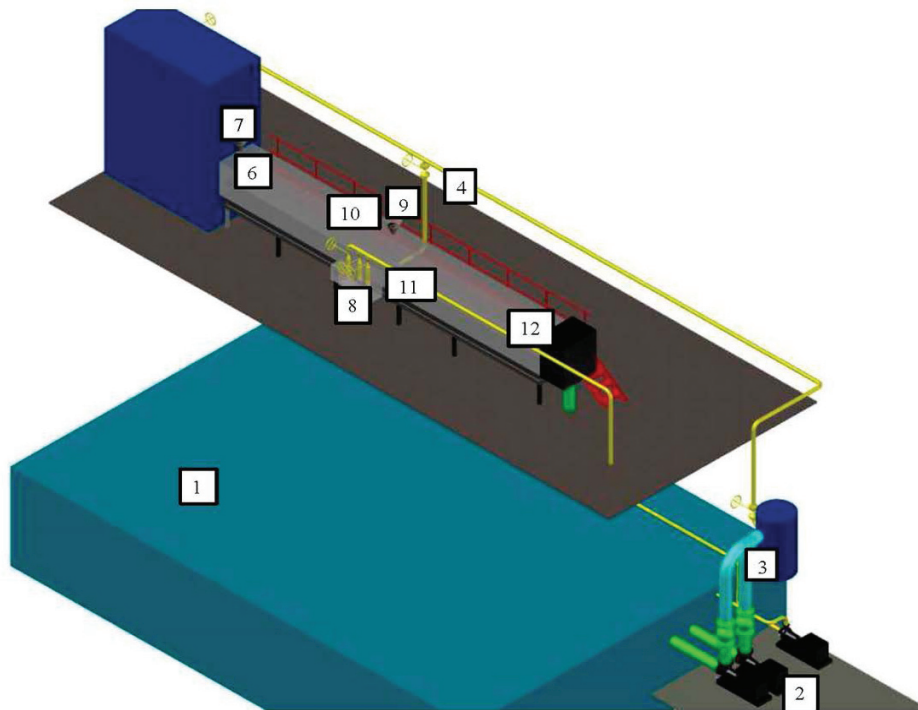


Fig. 1. The scheme of the laboratory hydraulic stand (tray)

During the tests, the model functionality has been checked at the admission of the estimated water discharge and regulation of water levels in the main supply chamber. Particular attention was paid to the methods of sediment sampling technique in the main supply chamber and intake pumps chamber.

Deposits sedimentation occurred throughout the main supply chamber. However, sediments inflow took place in the intake pumps chamber as well as their deposition there. Sediments are involved in the intake chamber due to the formation of eddy zone at the channel inlet chamber, which generates within the chamber series of closed eddies, contributing to the formation of deposits within the slurry intake chamber in emergency mode expectation (Figure 2).

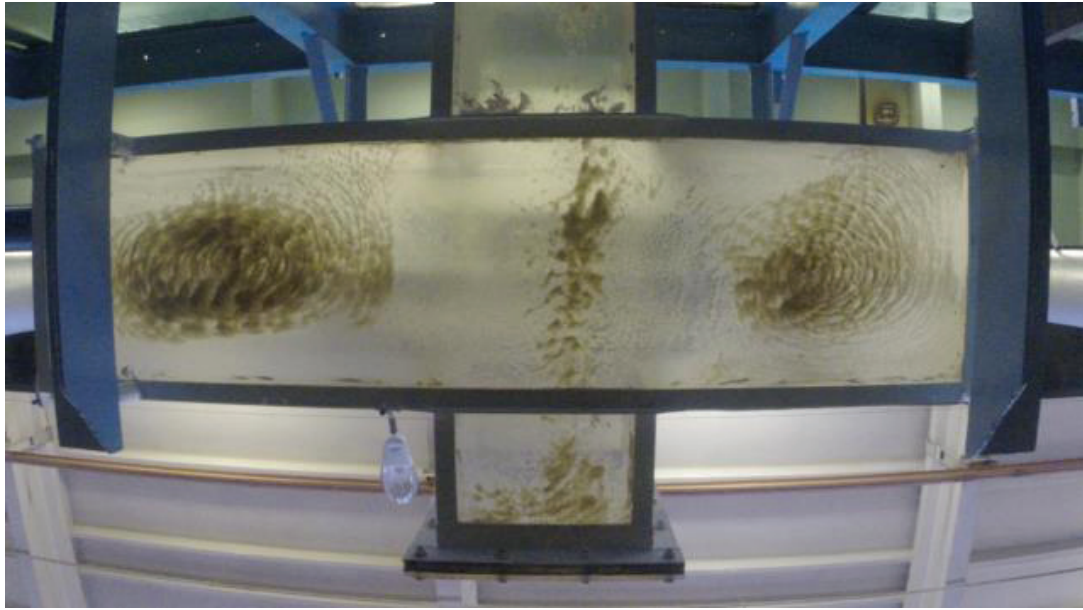


Fig. 2. Photo, bottom view (deposited sediments in backup intake chamber)

Based on the investigations, the following conclusions could be made. In the main supply chamber 4–6% of the sediments with the average particle size 0.025 mm were precipitated. The increasing of the average particle size up to 0.034 mm results in their deposition in chamber from 16 to 20%. We can say that the main supply chamber works as settling tank, where the part of incoming sediments, contained in the water, is deposited. At the same time there is a noticeable increasing of the particle size of deposited sediments. Figure 3 shows the curves of granule composition of sediments supplied to the model, and settled within the main supply chamber during the experiment. During the experiments it was found that the increasing of stream turbidity to the maximum does not change the proportion of sediments, which are deposited within the main supply chamber.

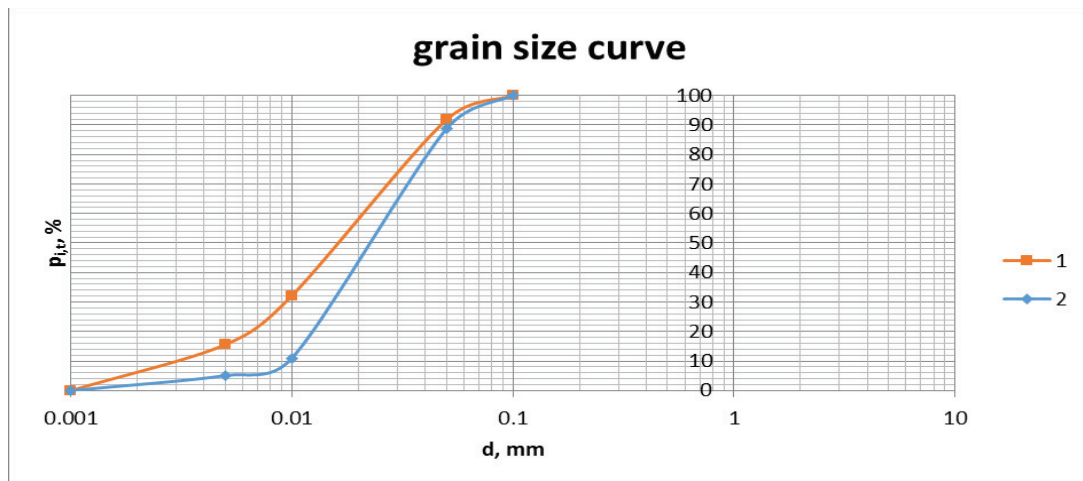


Fig. 3. Grain size curve



#### 4. Summary

Based on the results of investigation, technical solutions and operating modes were proposed to prevent the deposition of suspended sediments in the cooling system of NPP. For this purpose the forced sediments suspension by the flat bottom jets could be used as well as planned rotation of working and backup equipment.

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